Polymer Testing 32 (2013) 1154–1161

Contents lists available at ScienceDirect

Polymer Testing

journal homepage: www.elsevier.com/locate/polytest

Test equipment

Prototype and methodology for the characterization of the polymer-calibrator interface heat transfer coefficient

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ARTICLE INFO

Article history:
Received 27 May 2013
Accepted 8 July 2013

Keywords:
Interface heat transfer coefficient
Contact resistance
Extrusion
Calibration
Cooling

ABSTRACT

The extrusion of technical thermoplastics profiles generally uses a dry calibration/cooling system, composed by one or several calibrators in series. One of the major difficulties to be faced when modelling this important stage is an adequate prescription of the heat transfer coefficient, $h_{interface}$, between the plastic profile surface and the cooling medium, which must include the effect of the interface contact resistance. This is the motivation that led the present research team to develop a prototype calibration system and respective methodology for the characterization of $h_{interface}$ values which is able to consider a variety of conditions that can be found in extrusion practice. A modular construction was adopted for the calibration system, which allows studying easily the effect of several process parameters. In this work, the developed prototype system is described and its use is illustrated in the determination of $h_{interface}$ for the production of a polystyrene tape, under specific processing conditions.

1. Introduction

The extrusion of thermoplastic polymer systems is a continuous process used in the production of constant cross-section products, namely rods, sheet, films, pipes and profiles. Independently of the technical particularities demanded for the manufacturing of different types of products, in general, an extrusion process encompasses three main stages (see Fig. 1): i) the plastication stage, where the polymer is melted, homogenized and pumped into the extrusion die; ii) the forming stage, where the melt is shaped by an extrusion die; iii) the calibration/cooling stage, where the extrudate is cooled down and, eventually, calibrated, until a sufficiently low average temperature is reached that guarantees its shape downstream of the extrusion line. This stage in followed by a pulling device (or haul-off), which is responsible for the maintenance of a constant extrusion linear velocity, and a saw or winding device, to store the extrudate.

Thermoplastics have very low thermal diffusivity, of the order of 10^{-7} m.s^{-2}, which can bring some advantages in specific applications but makes all the processing stages involving heat exchanges with the polymer (heating or melting and, specially, cooling) critical. In fact, in continuous processes, such as extrusion, the cooling stage is usually responsible for limiting the maximum velocity of production, whereas in cyclic processes, such as injection moulding, thermoforming and blow-moulding it determines a significant part of the total cycle time (that can be of the order of 80%). Low thermal diffusivity is also responsible for the development of considerable thermal gradients during the cooling stage [1–4] and, consequently, for the development of stresses [5–13] that can be frozen in the product (generally referred as residual thermal stresses) that will affect negatively the mechanical performance of the product in use [14–18].

Unlike the other above mentioned types of extruded products, technical thermoplastic profiles may have a great

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http://dx.doi.org/10.1016/j.polymertesting.2013.07.006

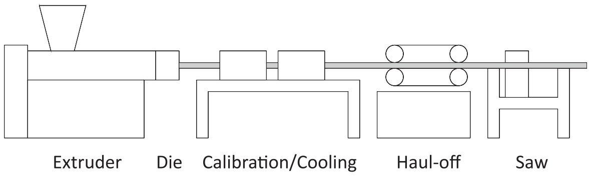

Fig. 1. Typical extrusion line for the production of pipes/profiles.

variety of shapes, uneven thickness and complexity, having varied and demanding applications such as window and door frames, decks for exteriors, blinds and electrical rails, for example. Therefore, these are the most challenging products in terms of the design of the corresponding forming/cooling tools, since each specific profile demands design of a tailored calibration system. A calibrator for extruded profiles comprises the forming cavity, a cooling system and a vacuum system as can be seen in Fig. 2.

Having in mind the above, the research team of the current work developed and validated an algorithm for the thermal design of calibrators for thermoplastic profiles, encompassing a non-isothermal 3D code based on the finite volume method (FVM) to model the thermal interchanges during the extrusion calibration/cooling stages, geometry and mesh generators, and an optimization routine aiming at determining the optimal cooling conditions [15–18]. A major difficulty to be faced in the use of the referred modelling code is an adequate prescription of the heat transfer coefficient, h, between the plastic profile surface and the cooling medium, i.e., calibrator internal walls, water or air, which must include the effect of the contact resistance. In fact, in a previous work [15] it was demonstrated that, despite the huge numbers of parameters influencing the performance of calibration systems (such as geometry of the cross section of the extrudate, polymer used, extrusion temperature, extrusion velocity, layout and diameter of the cooling channels, cooling water temperature, use of one or more calibrators in series, length of calibrators, distance between consecutive calibrators, material of construction of the calibrator, among others), the value adopted for the convection heat transfer coefficient, h, at the polymer-calibrator interface is one of the most influential parameters affecting the plastic profile cooling rate. The selection of the most appropriate value for h is still an unsolved problem, since it depends on many factors (surface finish of the calibrating cavity, level of vacuum used, difference of temperature between the surfaces of the polymer and the calibrating cavity, length of calibrator, cooling fluid used, etc.), is difficult to determine and, therefore, often appears in the literature with values ranging several decades (between 10 and 10 000 $W.m^{-2}.K^{-1}$) [19].

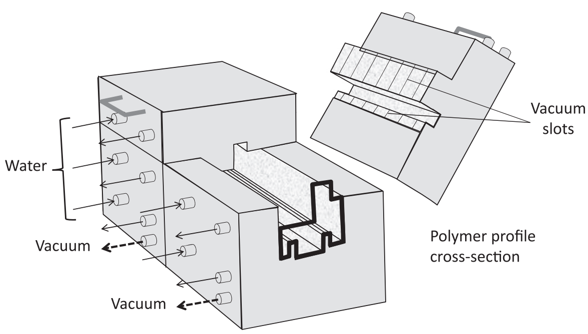

Fig. 2. Typical thermoplastic profile calibrator.

If the contact between two bodies is not perfect, a discontinuity in the temperature profile at their interface may occur (see Fig. 3(a)), its magnitude being proportional to the heat contact resistance that characterizes their interface. As described in [15], at the polymer-metal interface the heat flux is equal in both domains, its magnitude being a function of the temperature difference, thus governed by the following equations:

$$\begin{aligned} k_c\left(\frac{\partial T_c}{\partial n}\right)_{interface} &= -k_p\left(\frac{\partial T_p}{\partial n}\right)_{interface} \\ &= h_{interface}\left(T_p - T_c\right)_{interface} \end{aligned} \quad (1)$$

where T is the medium temperature, k is the thermal conductivity, $h_{interface}$ is the interface heat transfer coefficient and n is the normal vector of the surface. The subscripts p and c denote polymer and calibrator, respectively.

Therefore, the determination of the local heat contact resistance at the interface, or its inverse (corresponding value of the heat transfer coefficient), would require the measurement of the temperature of each surface at the interface. In extrusion calibration, this means that one would need to measure the temperature of the surface of the calibrator that is in contact with the polymer extrudate, and that of the polymer contact surface at the same location. This is not feasible since it would affect the heat transfer that takes place at the interface. Some alternative procedures have been developed to bypass this problem [20,21], which are described in the few published works related to the determination of convection heat transfer coefficients in polymer extrusion. One of the most complete studies is that carried out by Pittman and Whithan [20]. They studied the cooling of thick pipes, resorting to a special thermocouple unit encompassing four thermocouples that are pressed onto the pipe wall and inserted at different depths along the thickness of the thick pipe, which is carried down the length of the cooling stage. After the extrusion run, the precise location of the thermocouples was determined by X-ray. The process gave rise to the detailed evolution of the temperature of the pipe along the extrusion line (at different depths along its thickness) and enabled determination of the heat transfer coefficients corresponding to the different water tanks and in the annealing zones between them, after performing computer simulations of the experimental run. This solution proved to be quite useful for thick pipe extrusion where the cooling is performed by immersion in water, but could not be used in profile cooling, where the physical structure that supports the thermocouples (which is carried by the extrudate) would be in contact with the internal surface of the calibrator, affecting the heat transfer at the polymer-calibrator interface and bringing problems related to friction. Recently, a study on heat transfer during the cooling of profiles, using calibration, was published by Mousseau et al. [21]. These researchers developed a special instrumented calibration device which, together with a 2D

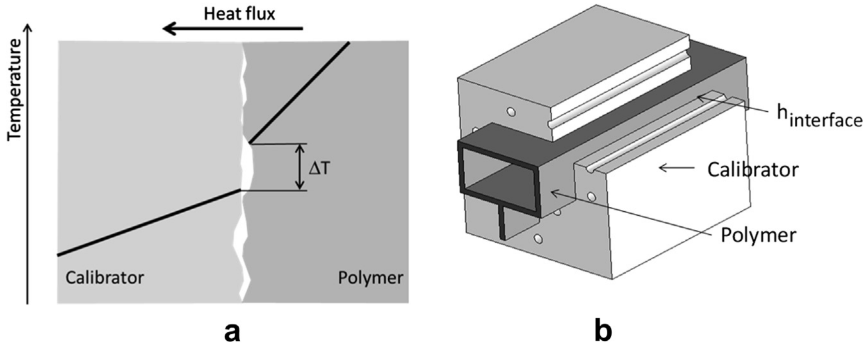

Fig. 3. Heat transfer between two surfaces that are not in perfect contact: (a) scheme; (b) the extrusion calibration case.

simulation heat transfer software used to solve the inverse problem, enabled determination of the heat fluxes at the polymer-calibrator interface. The work is fairly comprehensive and allows understanding all the heat transfer phenomena occurring during the cooling stage, but it seems too complicated for the determination of the thermal resistance at the polymer-calibrator interface. One of the reasons that complicates the analysis of the data gathered in this study is the fact that vacuum was applied on both sides of the plastic tape, which usually does not occur in practical extrusion, thus requiring the determination of the contact points between the tape and the surface of the calibrator along its length (for this purpose, the researchers used two similar calibrators: one transparent, for monitoring the contact points, and one metallic to obtain the data required). Additionally, to monitor the temperature distribution in the metal calibrator, the proposed methodology required the use of several thermocouples that were imbedded in the metal calibrator, making the application of the methodology to, for example, different materials of the calibrator or different geometries of the vacuum slots difficult.

Since the conditions in which the cooling stage takes place not only determine the production rate but also the final properties of extruded products, a simple, more versatile and proper characterization of the heat transfer coefficient is demanded, if realistic predictions of the temperature fields during the cooling stage and assessment of the effect of several system parameters are intended. This is the motivation that led the present research team to develop a prototype system and methodology for the characterization of values of h at the polymer-calibrator interface, $h_{interface}$, in a variety of conditions that can be found in extrusion practice. In this work, the developed methodology and prototype will be described in Section 2 and their use will be illustrated in Section 3, through a case study. Finally, the conclusions of the work are drawn in Section 4.

2. Prototype system and methodology for the determination of the heat transfer coefficient

2.1. Prototype system description

The prototype calibration system consists of an instrumented calibrator and the monitoring system that are placed in a conventional profile extrusion line, as shown in Fig. 4.

The extrusion line is comprised of the typical components employed, namely: extruder (1), extrusion die (2), prototype calibrator (3), vacuum pump (4), thermoregulator (5), flow-meter (6) and haul-off rolls (7). An infrared thermographic camera (8), ThermaCAM S, mounted on the top of the structure (9) that supports the prototype calibrator (3), can be axially displaced, and is employed to monitor the temperature distribution of the upper polymeric tape surface (10) before and after the prototype calibrator. The infrared thermographic camera uses software (ThermaCAM Researcher Professional 2.8 SER-2) that allows easy extraction of temperature distributions in specific regions from the recorded thermograms.

In service, the polymer melt pumped by the extruder (1) is shaped by the extrusion die (2) in order to produce a polymeric tape with controlled width and thickness, which is subsequently cooled in contact with the prototype calibrator (3), and finally pulled by the rolls (7) that establish the production linear velocity. The vacuum pressure imposed at the polymer-calibrator interface is controlled by the vacuum pump (4). The calibrator temperature is set by the thermoregulator (5), which controls the cooling water temperature, and flow-meter (6), which allows control of the cooling water flow-rate.

The prototype calibrator is modular, being composed of several building blocks. As shown in Fig. 5, these blocks are of two kinds: i) the inlet (3.1) and the outlet (3.3) blocks (ends of the calibration system), which are, necessarily,

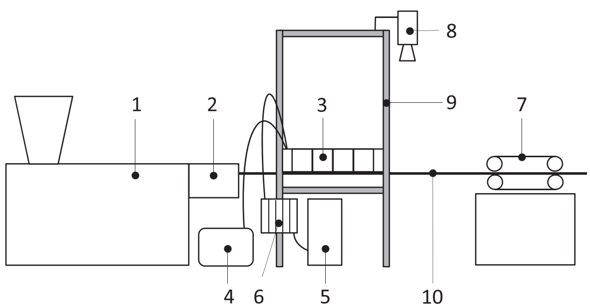

Fig. 4. Prototype system schematic view.

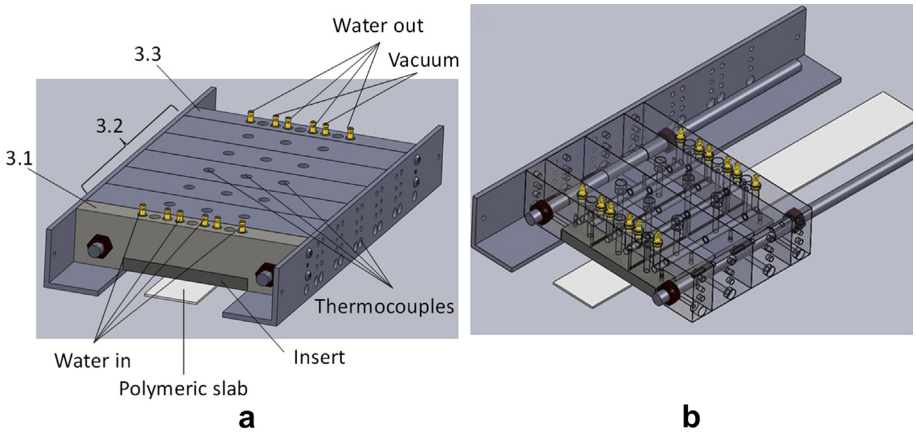

Fig. 5. Modular calibrator: (a) building blocks: 3.1 – inlet block; 3.2 – central blocks; 3.3 – outlet block; (b) layout of the cooling channels, vacuum channels and main clamping screws.

present in any configuration since they accommodate the links to the required services (water and vacuum), and the optional central blocks (3.2), all similar. The adopted modular construction allows to set the length of the calibration system, depending on the number of central blocks (3.2) employed.

Having in mind the current availability, the system can be used with a minimum calibration length of 50 mm (with only the two ends), a maximum of 300 mm (inserting the available five central blocks) and, in addition, intermediate lengths corresponding to the insertion of one to five central blocks. As can also be seen in Fig. 5(a), each block is composed of a main structure and an insert. Each block of the main structure accommodates four independent axial cooling channels, two vacuum channels and five thermocouples (three at the upper surface and one at each lateral surface) of 3 mm diameter, illustrated in Fig. 5. The sensing heads of the thermocouples are positioned against the surface of the insert in order to monitor the temperature of this component surface which, as explained below, will be used as a boundary condition in the modelling process required for determining $h_{interface}$. The temperature measured by the thermocouples is recorded via a data acquisition system. The insert block is screwed to the main block and can be manufactured with different materials and/or surface finishes, and can present a different number, location and dimensions for the vacuum slots. The blocks employed are fixed together by two clamping screws.

The full extrusion system in service is illustrated in Fig. 6(a) and a detailed outer view of the prototype calibrator is shown in Fig. 6(b).

2.2. *Methodology for the determination of the heat transfer coefficient*

As mentioned before, in the initial development phase of the methodology and prototype here presented, it was decided to eliminate the disturbances that would be induced by the measuring probes into the temperature field developed in the vicinity of the interface calibrator-polymer. As a consequence, the only probes used in the prototype are the small diameter thermocouples embedded in the calibrator main blocks. In service, the polymeric tape upper surface temperature was measured using an infrared thermographic camera focused at the entrance and exit regions of the calibrator, since measuring

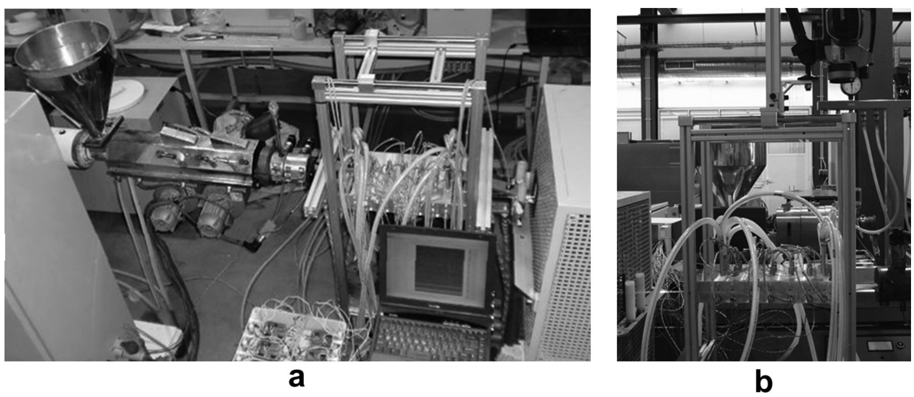

Fig. 6. Prototype system in service: (a) overview of the full system and (b) detailed view of the prototype calibrator.

this surface temperature inside the calibrator would also significantly affect the heat transfer conditions at the polymer-calibrator interface.

In the extrusion runs needed to determine $h_{interface}$, the modular calibrator is inserted and operated in a conventional extrusion line, as illustrated in Fig. 6(a). After reaching the steady state extrusion conditions (identified when the values read by all the thermocouples become steady) the infrared thermographic camera is focused on the upper inlet surface of the polymer tape and then on the upper outlet surface of the same tape. The measured temperature evolution of the mid-point tape upper surface is then extracted, from the recorded thermograms, along the extrusion axis.

The behaviour of the system is then modelled numerically considering a subsystem that is comprised of only the insert blocks and the polymeric tape, as can be seen in Fig. 7. The input data needed to solve this 3D heat transfer problem include those related to the system geometry, boundary conditions and relevant properties of the polymer and metal of construction of the calibration insert block (more details can be found elsewhere [15]).

In order to smooth the experimental uncertainties, the temperatures read by the thermocouples embedded in the calibrator block, shown in Fig. 5, were fitted through a second order function of the type:

$$T = T_0 + az + bw + cz^2 + dw^2 \quad (2)$$

where z and w are coordinates of the points where the temperature was measured (location of the thermocouples) in the extrusion direction and along the width of the calibrator (see Fig. 7(a)), respectively, and T_0, a, b, c and d are the fitting parameters.

The temperature function obtained (Eq. 2) is used as a Dirichlet boundary condition at the upper and lateral surfaces of the insert block, where the temperature was measured by the thermocouples.

The numerical modelling code is then used in an iterative manner in order to define the value of two parameters:

- Natural convection heat transfer coefficient (h_{air}) – obtained when the temperature evolution of the tape upper surface before the calibrator entrance fits the one measured experimentally;
- Heat convection coefficient at the polymer-calibrator interface ($h_{interface}$) – obtained when the temperature evolution of the tape upper surface after leaving the calibrator entrance fits the one measured experimentally;

The methodology to follow for the determination of both h_{air} and $h_{interface}$ is summarized in Fig. 8.

2.3. Potential

The experimental set-up described will enable determination of the heat transfer coefficient at the polymer-calibrator interface for different conditions relevant in extrusion practice, therefore allowing assessing the effects of:

- length of calibration (through the use of a different number of calibration modules);
- extrusion velocity (by varying the extruder screw speed and haul-off rolls velocity);
- quality of the polymer-calibrator contact (which can be varied through the surface finish of the calibrator insert surface, degree of vacuum applied or the number, location and dimension of the calibrator insert vacuum slots);
- temperature and flow rate of the cooling media (setting different temperatures at the thermo-regulator and flow rates at the flow meter, respectively);
- type of cooling media;
- extrusion temperature;
- construction material of the calibrator (changing the construction material of the calibrator insert).

With such a flexible system, it is expected, not only to characterize the values of the interface contact resistance, or the corresponding heat transfer coefficient, $h_{interface}$, for relevant extrusion conditions, but also to determine the relative importance of the main factors that are expected to influence its value.

3. Case study

The system developed was tested in an extrusion run using polystyrene, PS, Edistir N2560 and a calibration insert

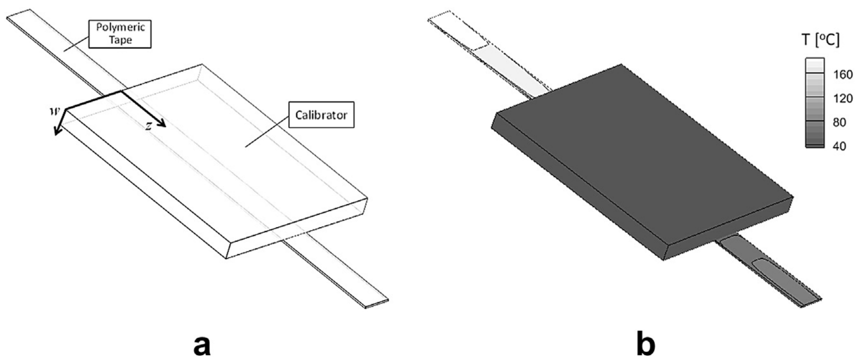

Fig. 7. Subsystem used for the numerical model of the process: (a) geometry and (b) computed typical temperature distribution.

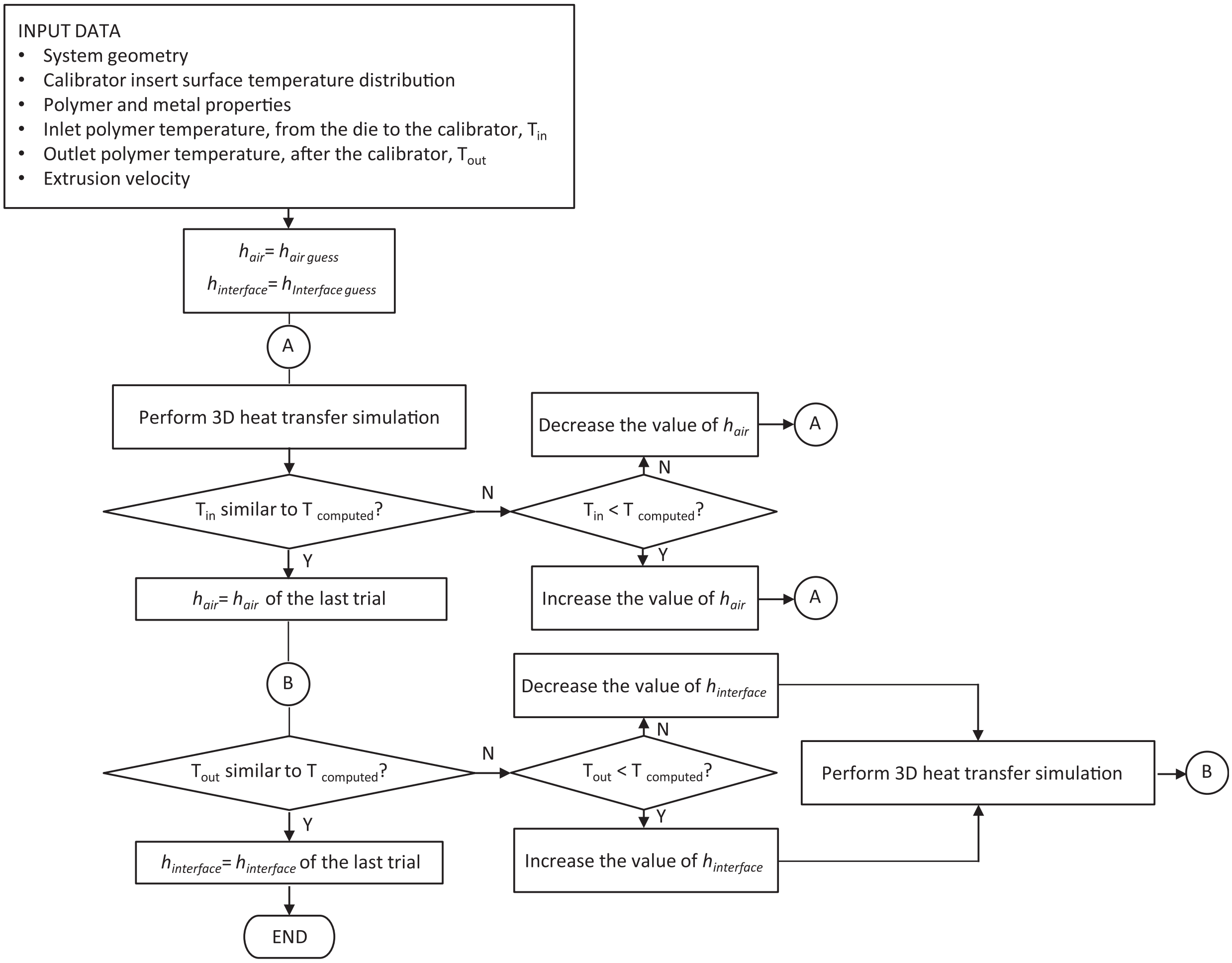

Fig. 8. Methodology for the determination of the values of the heat transfer coefficient at the polymer-calibrator interface ($h_{interface}$).

manufactured in aluminium. The modular calibrator was used with a total length of 300 mm (corresponding to the length of one inlet, one outlet and five central blocks). The distances between the die exit and the calibrator entrance and between the calibrator exit and the pulling unit were 135 mm and 110 mm, respectively. The relevant properties of the polymer and aluminium, the extrusion conditions and other input data needed to run the numerical modelling code are listed in Table 1.

For this case study, the parameters obtained after fitting the function used as boundary condition for the insert surface (Eq. 2), assumed the following values: T_0 = 43.61654 °C, a = −0.01629 °C.mm^{-1}, b = 0.0 0108 °C.mm^{-1}, c = 2.31763E-05 °C.mm^{-2} and d = −0.000 20551 °C.mm^{-2}.

The natural convection heat transfer coefficient, corresponding to the free surfaces of the polymer tape, h_{air}, and the heat transfer coefficient at the polymer-calibrator interface were determined using the methodology described in Section 2.2, resulting in the following values: h_{air} = 20 W.m^{-2}.K^{-1} and $h_{interface}$ = 435 W.m^{-2}.K^{-1}.

Fig. 9 shows the measured temperature evolution of the polymeric tape upper surface and the respective numerical predictions using the above heat transfer coefficients. The good correlation obtained between the numerical and experimental values evidences the quality of the fittings obtained.

Table 1
Data employed on the experimental run.

Property	Polymer (PS)	Aluminium
Density (kg.m^{-3})	1050	900
Thermal conductivity (W.m^{-1}.K^{-1})	0.17	237
Specific heat (kJ.kg^{-1}.K^{-1})	2.05	0.90
Extrusion conditions		
Extrusion temperature (°C)	210	
Linear extrusion velocity (m.s^{-1})	0.0263	
Other conditions		
Water temperature (°C)	30	
Room temperature (°C)	18	

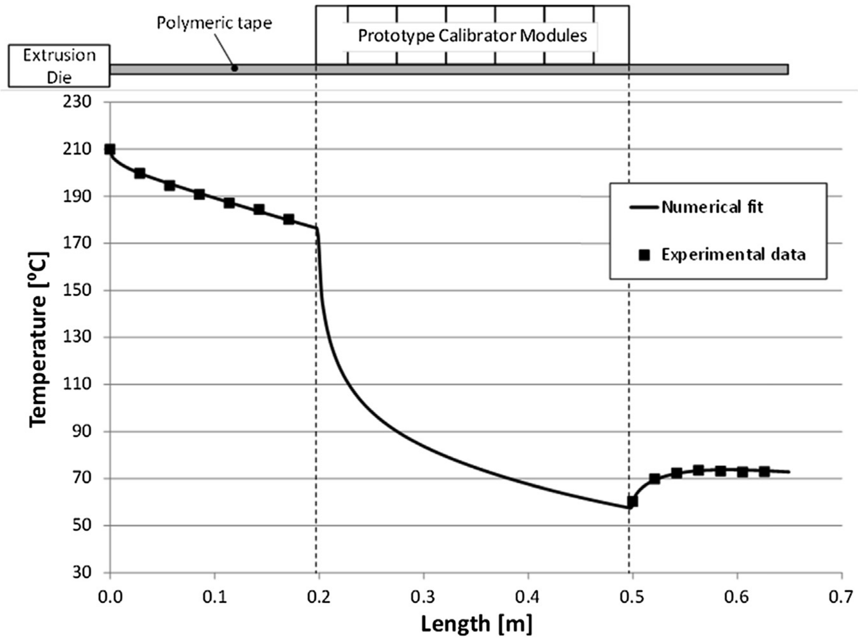

Fig. 9. Centre-line temperatures of the polymer tape upper surface: measured experimentally and computed by the numerical modelling code considering $h_{air} = 20$ W.m^{-2}.K^{-1} and $h_{interface} = 435$ W.m^{-2}.K^{-1}.

4. Conclusions

This works describes a novel prototype calibration system developed to determine the heat transfer coefficient at the polymer-calibrator interface ($h_{interface}$) in profile extrusion. The proposed methodology for the determination of $h_{interface}$ involves the employment of both the designed experimental system and a numerical modelling code where trial values of $h_{interface}$ are used, in an iterative process, until the numerical predictions fit properly the experimental measurements. A modular construction was adopted for the developed system, which allows studying easily the effect of several process parameters, namely: calibrator material, calibration length, extrusion velocity, quality of the polymer-calibrator contact, temperature and flow rate of the cooling media, type of cooling media, among others. The use of the developed system was illustrated on the determination of $h_{interface}$ for the production of a polystyrene tape under specific processing conditions.

Acknowledgements

The authors gratefully acknowledge funding from Fundação para a Ciência e a Tecnologia, FCT (COMPETE Program) under the projects FCOMP-01-0124 - FEDER-010190 (Ref. PTDC/EME - MFE/102729/2008) and FCOMP-01-0124 - FEDER-015126 (Ref. FCT PTDC/EME-MFE/113988/2009), and FEDER, via FCT, under the PEst-C/CTM/LA0025/2011 (Strategic Project - LA 25 - 2011-2012).

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